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14. ABSTRACT

This report results from a contract tasking University of Oslo as follows: The contractor will investigate magnetosphere and ionosphere coupling using meridian scanning photometers, spectrometers, all-sky imagers, and the incoherent scatter radar located on the island of Svalbard, Norway. The goal of this research proposal is to obtain a reliable understanding of disturbances in the polar ionosphere. Particular emphasis will be placed on mapping electron density patches near the cusp inflow region.

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FINAL REPORT

on

A COMPREHENSIVE STUDY OF POLAR CAP IONOSPHERIC PATCHES

by

Professor Jøran Moen, PI

15 SEPTEMBER, 2003

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1. BACKGROUND INFORMATION

1.1. Polar Cap Patches.

We have performing a detailed study of possible formation mechanisms of polar cap ionosphere patches near the cusp inflow region. Long lived plasma density enhancements referred to as polar patches, have been observed in the polar cap ionosphere for many decades. Crowley (1996) gave a formal definition of a plasma patch, which is useful: Plasma consentration enhancements should only be called patches if they are a factor 2 above the background density and at least 100 km in diameter. The patch/background ratio will reduce faster at lower altitudes where the recombination rate is higher. According to recombination rates given by Banks and Kockarts (1973) we can expect F-region plasma structures to last ~40 sec at 200 km altitude, ~10 minutes at 250 km altitude and ~1 hour at 300 km altitude (Walker et al., 1999). Hence, we know that enhanced densities in the E and lower F-region must be locally produced, whilst in the F-region above 250 km it is more difficult to address the source.

Ionospheric plasma patches have been observed moving in an antisunward direction throughout the polar cap. They are seen moving poleward into the polar cap on the dayside (*Foster and Doupnik*, 1984; *Foster*, 1989; *Lockwood and Carlson*, 1992; *Lockwood et al.*, 2001; *Opgenoorth et al.*, 2001; *Carlson et al.*, 2002), moving across the central polar cap (*Weber et al.*,1984; *Anderson et al.*,1988; *Sojka et al.*, 1993; 1994; *McEwen and Harris*, 1996; *Pedersen*, 2000) , and emerging from the polar cap into the nightside auroral oval (*Lockwood and Carlson*, 1992). In many studies, patches have been associated with regions of enhanced HF radar backscatter and so linked with the poleward-moving events seen by these radars (*Rodger et al.*, 1994a; b; *Milan et al.*, 2000; *Davies et al.*, 2002).

The mechanisms responsible for the formation of polar cap patches have been a matter of considerable debate. An association between patches and transient reconnection pulses has been suggested by a number of recent studies (*McCrea et al.*, 2000; *Lockwood et al.*, 2000; *Lockwood et al.*, 2001; *Opgenoorth et al.*, 2001; *Moen et al.*, 2001; *Nielsen et al.* 2003). Other studies suggest patches are linked to other phenomena, such as travelling convection vortices (*Valladares et al.*, 1994; 1999).

A key feature, which any theory of polar cap patches must explain, is why there exist minima between the regions of high plasma concentration, as opposed to them being appended directly to each other, so formimg a continuous "tongue" of enhanced ionization extending into the polar cap. Two different classes of mechanism have been

proposed: (1). the intermittent entry of flux tubes (and the frozen-in, photon-produced ionization) into the polar cap by time-varying convection; and (2). in-situ effects of precipitation and electric fields within the cusp/cleft region.

1.2. Intermittent entry of photon-produced ionization into the polar cap

Several conceptual and simulation models have reproduced polar cap patches using time-dependent convection in the presence of the photon-produced plasma concentration gradients associated with solar zenith angle (e.g., *Anderson et al.*,1988; *Sojka et al.*, 1993, 1994).

As pointed out by *Lockwood* (1993), it is not valid to impose time-varying convection patterns on a model of the coupled ionosphere-thermosphere system in an ad-hoc manner. The reason is that such a procedure will neglect the key magnetospheric distinction between open and closed field lines. Imposing an empirical model of the pattern of convection without this consideration will allow closed field lines to convect antisunward (without them first being opened or being subject to any viable viscous-like momentum transfer mechanism) and open field lines to convect sunward (without them first being reconfigured by tail or lobe reconnection).

Thus, although such simulations can produce patches by allowing plasma of varying photon-produced concentration to enter the polar cap, they are not revealing the real mechanism. This is because they are not constraining field lines to move into the polar cap through a realistic dayside reconnection merging gap, given that convection excitation is dominated by the production and loss of open flux by magnetic reconnection. *Lockwood and Carlson* (1992) provided a conceptual model of how the flow changes associated with pulsed reconnection could generate convecting polar cap patches, using the theory of ionospheric convection excitation by *Cowley and Lockwood* (1992). However, this mechanism relied on the OCB being in a close and particular proximity to the plasma concentration gradient associated with the day-night solar terminator and so cannot explain simultaneous patch production in the summer and winter polar caps, as has been observed by *Rodger et al.* (1994b). In addition, the requirement of this special condition is at odds with the fact that patches are present within the polar cap for such a large fraction of the time. *Lockwood et al.* (2000) provided a refinement of the Lockwood and Carlson model which would apply if the Y-component of the IMF is large in magnitude and events are longitudinally extensive. In this model, lower-concentration flux tubes arise from local times further away from noon and, once in the polar cap, they form the equatorward part of each patch of newly-opened flux generated by a reconnection pulse. Combined observations by the EISCAT Svalbard Radar (ESR) with the EISCAT VHF and CUTLASS radars (*Lockwood et al.*, 2000) and by the ESR with the Cluster and DMSP spacecraft (*Opgenoorth et al.*, 2001) provide evidence for this mechanism. Furthermore, fast azimuth scans by the ESR have shown plasma enhancements propagating into the polar cap (*Carlson et al.*, 2002).

1.3. In-situ effects in the cusp.

Rodger et al. (1994a) point out that plasma production by soft particle precipitation could be an important effect in patch production (*Whitteker*, 1977; *Watermann et al.*, 1994; *Davis and Lockwood*, 1996; *Millward et al.*, 1999; *Walker et al.*, 1999; *Vontrat-Reberac et al.*, 2001). In addition, Rodger et al. note that plasma loss rates are enhanced by strong ion drifts (*Schunk et al.*, 1975) and these have been both predicted and observed to generate significant depletions in the cusp region (*Balmforth et al.*, 1998; 1999; *Ogawa et al.*, 2001) within flow channel events (*Pinnock et al.*, 1993). Both these factors could be significant in introducing structure into the plasma concentrations on the timescales for flux tubes to enter the polar cap. To do so, it is necessary for some flux tubes entering the polar cap have undergone one or both of these processes to a greater degree than others. If all variables remained constant, other than the reconnection rate, then all newly-opened flux tubes reconnected at a given MLT would undergo the same sequences of precipitation and motion and thus the origin of the required structure is not obvious.

Debate about these two classes of mechanism has been considerable (e.g. *Rodger et al.*, 1994c; *Lockwood and Carlson*, 1994) and it is probable that both are required for a full understanding of patches. *McCrea et al.* (2000) used the ESR to study the field-aligned plasma concentration profiles within patches and found them to be different from the profiles of the nearby sunlit ionosphere but also different from those within the cusp.

2. INSTRUMENTATION

Optical instruments used for this project are a Meridian Scanning Photometer (MSP) and an all-sky imager both situated at Ny-Ålesund. The MSP comprises four photo multiplier tubes directed towards a turning mirror, which scans close to the magnetic meridian at an angle 45° west of geographic north. Every 20 second a scan is completed. The intensified all-sky imager is fitted with a rotating wheel containing different filters and observes the sky in 360° azimuth and 180° elevation. Every 15 second an image was taken alternating between 557.7 nm and 630.0 nm.

The solar wind characteristics were obtained from the ACE satellite. It maintains an orbit at the L1 libration point, positioned approximately at 1.5 million km from the Earth and 148 million km from the Sun, with a semi-major axis of 200,000 km. The solar wind is measured by particle detectors onboard the ACE satellite that measure the flux of the solar wind plasma upstream from the earth.

The auroral particle fluxes were supplied by the DMSP and NOAA satellites. DMSP satellites are in near polar sun synchronous orbits at an altitude of about 830 km above the Earth's surface. Each satellite crosses any point on the Earth up to twice a day and has an orbital period of about 100 minutes and does 14 revolutions per day. Each DMSP satellite measures a broad spectrum of atmospheric conditions. The SSJ/4 instrument is designed to measure the flux of charged particles as they enter the Earth's upper atmosphere from the near-Earth space environment. It consists of four electrostatic

analyzers that record electrons and ions (between 30eV and 30keV) as they flow past the spacecraft towards the earth (Hardy et al., 1984; Rich and Hairstone 1985). Also onboard DMSP satellites are the SSM magnetometers that measure magnetic fluctuations.

The NOAA 15 and 16 spacecrafts are part of the National Oceanic and Atmospheric Administration (NOAA). Both satellites are sun synchronous in nearly circular polar orbits at an altitude of 820 km. The NOAA 15 satellite carries two complements of particle instruments, the total energy detector (TED) and the medium energy proton and electron detector (MEPED). TED measures ions and electrons between 0.3 and 20 keV, in two viewing directions, one towards zenith and one 30° to zenith. This instrument was primarily designed to obtain the energy flux moment, but provides a crude ion and electron energy spectra as well. MEPED consists of two solid state detectors: one points towards zenith to detect particles precipitating into the auroral ionosphere, the other points 90° to zenith to detect particles that magnetically mirror above the atmosphere. Maximum measured energy for electrons are 1000 keV. The open/closed field line boundary is identified by the >30keV electron trapping boundary as proposed by Moen et al. (1998). Detailed description of the NOAA satelites and their sensors are given by Raben et al. (1995)

The EISCAT incoherent radar facilities consist of 3 radar systems. The UHF (933 MHz) and the VHF (224 MHz) located in northern Scandinavia, and the EISCAT Svalbard Radar (ESR) located in Longyearbyen, Svalbard. The UHF is the only three static incoherent scatter radar system in the world, with a transmitting and receiving antenna (32 m parabolic dish) located at Tromsø, and two additional receiving antennas in Sodankylä, Finland and Kiruna, Sweden. The Tromsø VHF system has a 5000 m^2 reflector with a meridional beam steering. The ESR is the last generation incoherent radar located within the polar cap. The system comprises two parabolic dish antennas sharing the same transmitter and receiver system, working at 500 MHz. ERS-1, is a 32-m diameter antenna, which can swing 540° in azimuth and from 0 to 180° in elevation. ERS-2, 42 m in diameter, is a fixed beam oriented along the magnetic field line. The ERS radar facility is located on the mountain of Mine 7, within 6 km from the Longyearbyen Auroral Station. With the three EISCAT radar systems working together it is possible to provide a spatial radar coverage of up to ~20° in magnetic latitude, with high time and spatial resolution.

3. SCIENTIFIC RESULTS

We have been undertaking a comprehensive study of plasma density patches associated with cusp auroral activity observed by EISCAT VHF on 23 November 1999, the combination of EISCAT VHF and optics on 17 December 2001, and by the combination of EISCAT Svalbard Radar and optics on 20 December 1998. We have observed two categories of plasma patches: 1) associated with poleward moving auroral forms, and 2) patches which have formed well equatorward of the auroral zone. In both cases, the electron density was much higher than would be expected from particle impact ionisation. Hence, for both categories, plasma patches have apparently been chopped off

the tongue of ionisation (photo-ionized) by some mechanism. Patch formation seems to be related to boundary movements associated with magnetopause reconnection. Different mechanisms to explain the minima between patches have been tested, and the plasma concentration gradients on the edges of the larger patches appear to arise mainly from local time variations in subauroral plasma. The work on this proposal has resulted in 5 papers of which abstracts are listed below.

Paper 1: Annales Geophysicae, in press

Evidence for solar-production as source of polar-cap plasma

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ABSTRACT

The focus of the study is a region of enhanced ionospheric densities observed by the EISCAT Svalbard radar in the polar F-region near local magnetic noon under conditions of IMF $Bz<0$. Multi-instrument observations using optical, spacecraft and radar instrumentation together with radio tomographic imaging have been used to identify the source of the enhancement and establish the background ionospheric conditions. Soft-particle precipitation was ruled out as a candidate for the production. Tomographic observations identified a latitudinally restricted region of enhanced densities at sub-auroral latitudes, distinct from the normal mid-latitude ionosphere, which was likely to be the source. The evidence suggested that the increased sub-auroral densities were photoionisation produced at the equatorward edge of the afternoon high-latitude cell, where the plasma is exposed to sunlight for an extended period as it flows slowly sunward toward magnetic noon. It is proposed that this plasma once in the noon sector was drawn antisunward by the high-latitude convection toward polar latitudes where it was identified by the EISCAT Svalbard radar. The observations are discussed in terms of earlier modelling studies of polar patch densities.

Paper 2: Reviewed by Annales Geophysicae and revised.

Patch formation in relation to cusp auroral activity

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ABSTRACT

In December 2001 a joint Norwegian and UK patch campaign was carried out involving EISCAT and ground optical observations of the cusp/cleft ionosphere above Svalbard. On 17 December plasma patches with densities up to 10^{12} m^{-3} was observed close to the convection throat by the EISCAT VHF radar. During most of the experiment IMF B_Y was strongly positive and B_Z negative. This paper focuses on the period between 07:10 and 09:15 UT when various plasma structures were observed. Electron density increased with local time from 06:45 until 08:15 UT and the auroral activity region was found far south due to southward IMF and magnetopause reconnection. Between 07:10 and 07:45 UT plasma structures associated with PMAFs (Poleward Moving Auroral Forms) were observed. The plasma was found partly south of the open/closed field line boundary (OCB) and no increase in plasma density was associated with the equatorward boundary of the 630.0 nm emissions. Therefore we conclude that these structures mainly were formed as a result of transported, solar ionized plasma. Between 08:10 and 09:15 UT larger and denser patches appeared. The patches were observed south of the aurora but poleward of the OCB. Each patch in the sequence appeared to be related to a poleward relaxation of the 630.0 nm emission boundary, but were formed south of the auroral activity region. This indicates that low energy particle precipitation cannot be the major source of the plasma patches in question and that the patches more likely were chopped off the Tongue of Ionization (TOI) by flux transfer events (FTEs). On the basis of observations and thermal considerations we find that in general an increase in plasma density caused by local precipitation is unlikely to exceed 3×10^{11} m^{-3}

Paper 3: Reviewed by Annales Geophysicae and revised.

The Dynamics and Relationships of Precipitation, Temperature and Convection Boundaries in the Dayside Auroral Ionosphere

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ABSTRACT

A continuous band of high ion temperature, which persisted for about 8 hours and which zigzagged north-south across more than five degrees in latitude in the dayside (7-15 MLT) auroral ionosphere, was observed by the EISCAT VHF radar on November 23, 1999. Latitudinal gradients in the temperature of the F-region electron and ion gases (T_e and T_i, respectively) have been compared with concurrent observations of the particle precipitation and the field-perpendicular convection by DMSP satellites. This in order to reveal a physical explanation for the persistent band of high Ti, and to test the potential role of T_i and T_e gradients as possible markers for the open-closed field line boundary. The north/south movement of the equatorward T_i boundary was found consistent with contraction/expansion of the polar cap due to unbalanced dayside and nightside reconnection. Sporadic intensifications in T_i, recurring on ~10 minute timescales, indicate that frictional heating was indeed modulated by time-varying reconnection, and the band of high T_i was located on open flux. However, the equatorward T_i boundary was not found to be a close proxy of the open-closed boundary. The closest definable proxy of the open-closed boundary is the magnetosheath electron edge observed by DMSP. The distance between the T_i boundary was ~200 km for the DMSP pass around ~50 km for the subsequent pass around 12 MLT. Although T_e appears sensitive magnetosheath electron fluxes it is not found to be a suitable parameter for routine tracking of the open-closed boundary, as it involves case dependent analysis of the thermal balance. Finally, we have documented a region of newly opened sunward convecting flux. This region is situated between the convection reversal boundary and the magnetosheath electron edge defining the open-closed boundary. This is consistent with a several-minutes delay between the arrival of the first (super Alfvénic) magnetosheath electrons and the response in the ionospheric convection, conveyed to the ionosphere by the interior Alfvén wave. It represents a candidate footprint of the low-latitude boundary mixing layer on sunward convecting open flux.

Paper 4: Submitted to Annales Geophysicae

Motion of the dayside polar cap boundary during substorm cycles: I. Observations of pulses in the magnetopause reconnection rate

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ABSTRACT
Using data from the EISCAT VHF radar and DMSP satellite passes, we study the motion of the dayside open-closed field line boundary during two substorm cycles. The satellite data show that the motions of ion and electron temperature boundaries in EISCAT data, as reported by *Moen et al.* [2003], reflect motions of the open-closed field line boundary at all MLT throughout the dayside auroral ionosphere. The boundary is shown to erode equatorward when the IMF points southward, consistent with the effect of magnetopause reconnection. During the substorm expansion and recovery phases, the dayside boundary returns poleward, whether the IMF points northward or southward. However, the poleward retreat was much faster during the substorm for which the IMF had returned to northward than for the substorm for which the IMF remained southward – even though the former substorm is much the weaker of the two. These poleward retreats are consistent with the destruction of open flux at the tail current sheet. Analysis of the peak ion energies at the equatorward edge of the cleft/cusp/mantle dispersion seen by the DMSP satellites identifies the dayside reconnection merging gap to extend in MLT from about 9.5 to 15.5 hrs for most of the interval. Analysis of the boundary motion, and of the convection velocities seen near the boundary by EISCAT, allows calculation of the reconnection rate (mapped down to the ionosphere) from the flow component normal to the boundary in its own rest frame. This reconnection rate is not, in general, significantly different from zero before 06:45 UT (MLT<9.5 hrs) – indicating that the X line footprint expands over the EISCAT field-of-view to earlier MLT only occasionally and briefly. Between 06:45 UT and 12:45UT (15.5<MLT<9.5 hrs) reconnection is continuously observed by EISCAT, confirming the (large) MLT extent of the reconnection footprint deduced from the DMSP passes. As well as direct control by the IMF on longer timescales, the derived reconnection rate variation shows considerable pulsing on timescales of 2-20 min. during periods of steady southward IMF.

Paper 5: Submitted to Annales Geophysicae

Motion of the dayside polar cap boundary during substorm cycles: II. Generation of poleward-moving events and polar cap patches by pulses in the magnetopause reconnection rate

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ABSTRACT:
Using data from the EISCAT VHF and CUTLASS HF radars, we study the formation of ionospheric polar cap patches and their relationship to the magnetopause reconnection pulses identified in the companion paper by *Lockwood et al.* (2003b). It is shown that the poleward-moving, high-concentration plasma patches observed in the ionosphere by EISCAT on 23 November 1999, as reported by *Davies et al.* (2002), were associated with corresponding reconnection rate pulses. However, not all such pulses generated a patch and only within a limited MLT range (11-12 hrs) did a patch result from a reconnection pulse. Three proposed mechanisms for the production of patches, and of the concentration minima that separate them, are analysed and evaluated: (1) concentration enhancement within the patches by cusp/cleft precipitation; (2) plasma depletion in the minima between the patches by fast plasma flows; and (3) intermittent injection of photoionisation-enhanced plasma into the polar cap. We devise a test to distinguish between the effects of these mechanisms. Some of the events repeat too frequently to apply the test. Others have sufficiently long repeat periods and mechanism (3) is shown to be the only explanation of three of the longer-lived patches seen on this day. However, effect (2) also appears to contribute to some events. We conclude that plasma concentration gradients on the edges of the larger patches arise mainly from local time variations in the subauroral plasma, via the mechanism proposed by *Lockwood et al.* (2000).

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